Effect of Electrode Loss on the Dynamic Range of Linearized Directional Coupler Modulators

George A. Brost, Richard Michalak, Paul Payson, and Kevin Magde

***Abstract*—Numerical simulations were used to study the effect of electrode loss on the two-tone spur-free dynamic range (SFDR) of analog photonic links with linearized directional coupler modulators. Radio-frequency loss in the traveling wave electrode significantly limits the frequency bandwidth over which this class of electrooptic modulator can effectively enhance the SFDR.**

***Index Terms*—Electrooptic modulation, optoelectronic devices.**

I. Introduction

THE directional coupler modulator (DCM) is of interest for applications of analog photonic links requiring greater spur-free dynamic range (SFDR) than that which is obtained from a standard Mach–Zehnder modulator (MZM). The SFDR of a photonic link depends on the performance of all its components, but is generally limited by the linearity of the modulator. Modifications to the basic DCM architecture, such as inclusion of additional bias structures can, in principle, improve the two-tone SFDR to over 130 $\mathrm{dB \cdot Hz^{2/3}}$. Numerous variations of the modified DCM have been proposed [1]–[5]. Modeling of some of these linearized architectures showed that although the gain could have a broad frequency response, the SFDR bandwidth was limited by velocity mismatch [6], [7]. However, the earlier analyses did not include the effect of electrode loss on the transfer characteristics of the DCM. In this letter, we analyze the effect of electrode loss on the frequency dependence of the two-tone SFDR in modified directional couplers by numerical simulations of the photonic link. As we show below, electrode loss may be the most significant factor limiting the SFDR frequency bandwidth of linearized DCMs.

II. Link Model

The two-tone SFDR of a photonic link depends upon the parameters of all of the components. For our analysis, we assumed a simple link with parameters that isolate the effect of modulator nonlinearity: Laser power: 100 mW; laser relative intensity noise: −165 dB/Hz; photodetector responsivity: 0.8 A/W; detector impedance: 50 Ω; modulator impedance: 50 Ω; and modulator insertion loss: 3 dB. We assume that the modulator electrooptic effect is such that an interaction length of 2 cm would have a half-wave voltage (V_π) of 2 V. Velocity mismatch was assumed to be negligible.

The modulator response was simulated numerically following the approach of Farwell and Chang [7]. This approach was based on using a cascade of 2 × 2 matrices for modeling the output intensity of the coupled waveguides. The matrix expression relating the optical fields at the input and output channels of a section of coupled waveguide used were determined from the solution of the coupled mode equations

$$\begin{bmatrix} R_{\mathrm{out}} \\ S_{\mathrm{out}} \end{bmatrix} = A \begin{bmatrix} R_{\mathrm{in}} \\ S_{\mathrm{in}} \end{bmatrix} = \begin{bmatrix} a_{11} & -ia_{12} \\ -ia_{12} & a_{11}^{*} \end{bmatrix} \begin{bmatrix} R_{\mathrm{in}} \\ S_{\mathrm{in}} \end{bmatrix} \tag{1}$$

where

$$a_{11} = \cos\left[\frac{\pi}{2} s \sqrt{1 + \left(\frac{V}{V_S}\right)^2}\right] + iV \frac{\sin\left[\frac{\pi}{2} s \sqrt{1 + \left(\frac{V}{V_S}\right)^2}\right]}{\sqrt{V^2 + V_S^2}} \tag{2}$$

and

$$a_{12} = \frac{\sin\left(\frac{\pi}{2} s \sqrt{1 + \left(\frac{V}{V_S}\right)^2}\right)}{\sqrt{1 + \left(\frac{V}{V_S}\right)^2}}. \tag{3}$$

Here V is the applied voltage, s is the ratio of the physical length of the section to the coupling length of the coupled waveguides, and V_S is the switching voltage, which is the voltage required to induce a π phase change in one coupling length of the waveguide. The active region of the modulator was subdivided into M sections. The voltage on the electrode was considered to be uniform within each section.

The SFDR was calculated by simulating the application of a two-tone signal to the modulator. The voltage applied to the kth section of the modulator was

$$V_k = V_B + \mathrm{RF}_k \sin\left[2\pi(f_1 + f_2)t\right] \tag{4}$$

where V_B is a dc bias voltage, RF_k is the signal voltage across the kth segment, f_1 and f_2 are the fundamental frequencies of the applied signal, and t is time. The input signal was time sampled N times and the sequence of N intensity values was transformed using an N-point fast Fourier transform. The magnitudes of the fundamental and spurious signals were obtained from the values of the appropriate output frequencies, which depended on the sampling parameters. We used $N = 128$, a time interval of $T = 1/128$, $f_1 = 9$ and $f_2 = 10$. The third-order intermodulation component at frequency $(2f_1 - f_2)$ was used to compute the SFDR. The two-tone SFDR was determined by the ratio of the fundamental output power to the power in the third-order intermodulation spur at the input power where the third-order modulation spur was equal to the link noise floor.

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14. ABSTRACT

Numerical simulations were used to study the effect of electrode loss on the two-tone spur-free Dynamic range (SFDR) of analog photonic links with linearized directional coupler modulators. Radio-frequency loss in the traveling wave electrode significantly limits the frequency bandwidth over which this class of electro-optic modulator can effectively enhance the SFDR.

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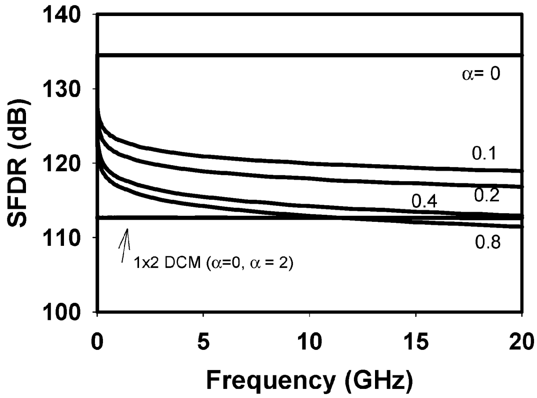

Fig. 1. Frequency dependence of SFDR for the 1 × 2 DCM ($s = 0.707$), and the Y-fed two-section DCM with different electrode loss parameters. Modulator length is 2 cm.

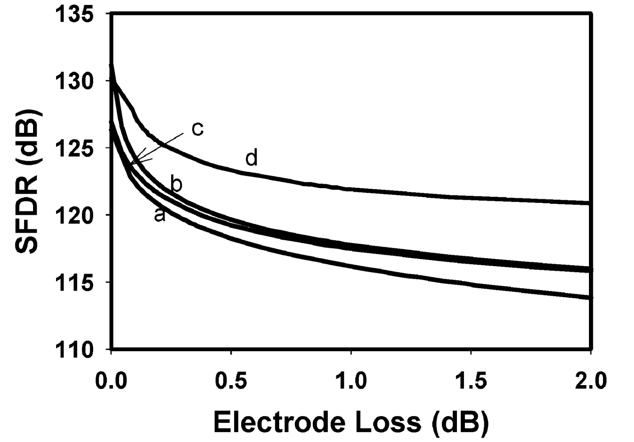

Fig. 2. SFDR as a function of electrode loss for (a) Y-fed two-section DCM (b) 2 × 2 DCM with two bias sections, (c) Y-fed, DCM with one bias section, and (d) Y-fed DCM with $s = 2.86$.

The SFDR results reported here are relative to a 1-Hz bandwidth noise floor.

III. Results

We consider first a 1 × 2 (Y-fed) DCM. An attractive feature of this device is that it is automatically biased to operate at the quadrature point. When $s = 0.707$, the 1 × 2 DCM can switch transmission between 0% and 100%, and has a transfer function similar to an MZM. In Fig. 1, we plot the frequency response for the two-tone SFDR for a 2-cm-long modulator and for the radio-frequency (RF) loss parameter $\alpha = 0$, and $\alpha = 2$ dB/cm/$\sqrt{F}$ (GHz). The SFDR is quite insensitive to the electrode loss. When $s \approx 2.86$, the 1 × 2 DCM has a transfer function with improved linearity. Talykaev and Ramaswamy [5] suggested a further modification to the 1 × 2 DCM that could significantly increase the SFDR, but with greater tolerance to fabrication errors. The so-called two-section Y-fed DCM has a second modulation section which has the opposite sign. The transfer characteristics strongly depend upon the s values of each section. When $s_1 = 2.32$ and $s_2 = 1.05$, this modulator operates in a highly linear regime, resulting in a link SFDR > 130 dB which is over 20-dB increase in SFDR compared to the standard DCM and MZM. This modulator is an example of a class of modified DCMs that utilize multiple coupling sections, some of which may have only a dc bias, to linearize the transfer function. In Fig. 1, we plot the calculated gain and SFDR versus frequency for different values of α. The frequency bandwidth of the SFDR of the linearized DCM is very sensitive to electrode loss.

These results are typical of most other linearized modified DCM designs as well. This is shown in Fig. 2 where we plot the calculated SFDR as a function of the total RF loss across the electrode for four different linearized DCMs: the Y-fed two-section DCM; two other variations of multisectioned linearized DCMs; a three-section DCM that consists of a 2 × 2 DCM followed by two DCM bias sections to which only a dc bias is applied [1], and a two-section DCM which consists of a Y-fed DCM followed by one dc bias section; the 1 × 2 DCM with $s \approx 2.86$.

The results shown in Figs. 1 and 2 above suggest that it is necessary to keep the electrode loss below 0.3 dB to realize the potential benefit of linearized DCMs. If we consider even an optimistic loss coefficient as low as $\alpha = 0.3$ dB/cm $(\mathrm{GHz})^{-1/2}$, device sizes would need to be kept below about 2 mm of interaction length to be useful over a broad frequency range. The issue then becomes one of utility. In most high-fidelity photonic link applications, the link gain and noise figure are important considerations. The effective V_π of such a modulator fabricated with lithium niobate would be on the order of 100 V resulting in unacceptable performance characteristics [8]. This high effective V_π value is due in part to the limited electrooptic coefficient of 30 pm/V. It is also due in part to the reduced modulation efficiency which is typical of the linearized architecture. For the modified DCM, the effective V_π is about a factor of three to four greater than an MZM of the same interaction length. For devices with such short interaction lengths, this dictates the use of electrooptic materials with much higher electrooptic coefficients than are currently available.

We note that we have observed one exception to the electrode loss sensitivity of linearized DCMs. The suboctave DCM is a standard 2 × 2 DCM which has a length of one coupling length $(s = 1)$ and has a dc bias point that minimizes the third-order intermodulation distortion [6]. Although quite sensitive to bias, our simulations have shown that the high SFDR of this modulator (approximately 138 dB) is quite insensitive to electrode loss.

The application of a dc bias to the electrode of the modulator can tune the transfer characteristics to compensate for the distortions due to electrode loss. This is shown in Fig. 3. Here we plot the calculated SFDR as a function of frequency for different modulator lengths of the Y-fed two-section DCM with $s_1 = 2.32$ and $s_2 = 1.0$, as for the previous calculations. The electrode loss coefficient was $\alpha = 0.6$ dB/cm/$\sqrt{F}$(GHz). In each case, the bias voltage was set to optimize the SFDR for a frequency near 10 GHz. We note that this yielded a higher peak SFDR than the unbiased results shown above, as we did not attempt to optimize the peak SFDR there. These results show that in principle it is possible to achieve highly linear performance at microwave frequencies over a significant frequency bandwidth without requiring very small electrode lengths. In the example shown in Fig. 3, a 1-cm-long interaction length can support an

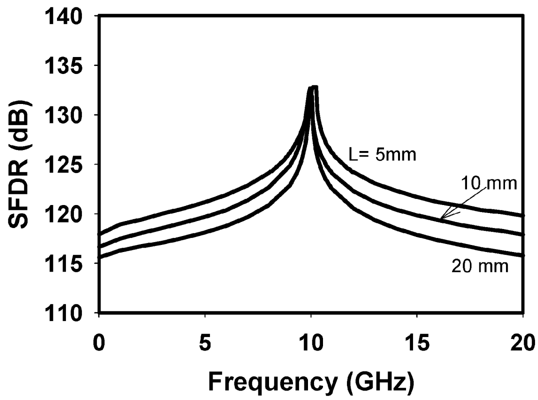

Fig. 3. Frequency dependence of the SFDR for different modulator electrode lengths of the Y-fed two-section DCM and $\alpha = 0.6$ dB/cm/$\sqrt{F}$(GHz) with bias optimized for high SFDR near 10 GHz.

SFDR > 120 dB over a frequency bandwidth of almost 8 GHz, and a 125-dB SFDR at over 1 GHz of bandwidth. Implementation would require the ability to set and control the bias voltage. The approach of using a low-frequency pilot tone would not apply here, as the bias voltage is frequency specific.

IV. Summary

We have used numerical simulations to analyze the effect of electrode loss on the two-tone SFDR of analog photonic links employing linearized DCMs. The results show that the frequency bandwidth over which this class of modulator can provide significant enhancement to the SFDR is severely limited by the electrode loss. Interaction lengths of less than 2 mm together with very low loss electrodes will likely be required for wide-band performance. This in turn will require the development of new electrooptic materials with significantly higher electrooptic effects than current state of the art materials to overcome the loss in modulation efficiency. Linearized DCMs may be tuned to achieve high SFDR at microwave frequencies by applying an appropriate bias voltage to compensate the distortions resulting from the electrode loss.

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